Development of a Single-Layer Nb_3Sn Common Coil Dipole Model

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***Abstract*— A high-field dipole magnet based on the common coil design was developed at Fermilab for a future Very Large Hadron Collider. A short model of this magnet with a design field of 11 T in two 40-mm apertures is being fabricated using the react-and-wind technique. In order to study and optimize the magnet design two 165-mm long mechanical models were assembled and tested. A technological model consisting of magnet straight section and ends was also fabricated to check the tooling and the winding and assembly procedures. This paper describes the design and technology of the common coil dipole magnet and summarizes the status of short model fabrication. The results of the mechanical model tests and comparison with FE mechanical analysis are also presented.**

***Index Terms*—common coil dipole, mechanical model, Nb_3Sn, superconducting accelerator magnet, technological model.**

I. Introduction

A single-layer common coil dipole magnet [1] was developed at Fermilab for a future Very Large Hadron Collider [2]. The magnet was designed to provide a 10.4 T nominal field in two 40-mm apertures at operation temperature of 4.5 K. It is based on Nb_3Sn superconductor and react-and-wind fabrication technique [3]. This magnet has several innovative design and technological features such as single-layer racetrack coils, a 22-mm wide 60-strand Rutherford-type cable made of 0.7-mm Nb_3Sn strands, and stainless steel coil support structure reinforced by horizontal bridges inserted between coil blocks [4]. Both left and right coils are wound simultaneously into the collar structure and then impregnated with epoxy.

The development of magnet design has been completed and the short model R&D program to study and optimize the common coil magnet design and react-and-wind technology has been started. This program consists of different steps such as cable development, fabrication and tests of simple racetrack coils as well as common coil mechanical and technological models, and finally fabrication and tests of series of common coil short models. Up to now two racetracks have been fabricated and tested. The results are reported elsewhere [5], [6].

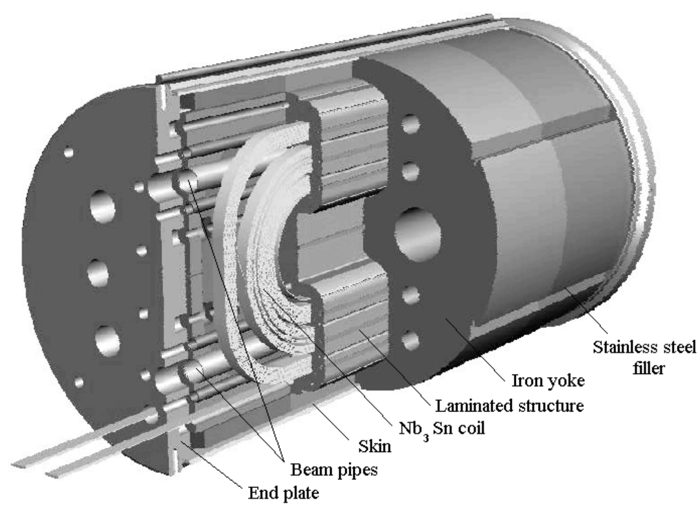

Fig. 1. Common coil dipole cold mass.

Two short mechanical models and technological model have been also assembled and tested. Based on the obtained results necessary corrections in the design have been introduced and model fabrication has been started. This paper describes the design and technology of the common coil dipole magnet and summarizes the status of short model fabrication.

II. Magnet Design

The 3D view of the magnet cold mass is shown in Fig.1. The magnet design is based on single-layer flat racetrack coils shared between two apertures. The coils are made of rectangular Rutherford-type cable with a width of 21.09 mm and a thickness of 1.245 mm. The cable consists of 60 strands, each 0.7 mm in diameter. The nominal cable insulation is 0.10 mm thick. Each coil consists of 58 turns grouped into 3 blocks with 18, 22, and 18 conductors respectively. The pole blocks are shifted horizontally towards the apertures by 5 mm with respect to the middle blocks to minimize geometrical harmonics. The gap between the pole blocks of 40 mm determines the magnet aperture. The design was optimized for the react-and-wind technique. This approach suggests the minimum-bending radius of 90 mm for the chosen cable size and thus restricts the minimum aperture separation to 290 mm. The iron yoke is split vertically into two pieces. Special holes correct the iron saturation effect.

The mechanical design developed for this magnet uses an effective stress management strategy to protect brittle Nb_3Sn cable and other structural elements from the over-load [4]. Coil blocks, surrounded by the 0.5 mm thick electrical insulation, are placed inside a strong support structure formed by stainless steel collar laminations in straight section and by solid stainless steel parts at both ends. During fabrication the structure provides the required vertical pre-stress and protects the coil from an over-compression in horizontal and vertical directions while during operation it prevents an accumulation and transfer of the vertical Lorentz forces from the pole blocks to the mid-plane blocks. It also intercepts a significant part of the horizontal Lorentz force components reducing stresses in the yoke and the relatively thin skin to a level well below their yield stresses. The calculated stress in the coil at all conditions is less than the degradation limit for the brittle Nb_3Sn cable.

The described mechanical design requires simultaneous winding of both coils directly into the support structure and then impregnating coils with epoxy inside the structure. The collared coil assembly is placed inside the iron yoke surrounded by a 10 mm thick stainless steel skin. The stainless steel skin via the iron yoke provides the horizontal pre-compression of the collared coil. Thick 50 mm end plates welded to the skin with bullets restrict the longitudinal motion of the coil ends.

III. Mechanical Models

The magnet mechanical concept, the main components such as the cable, insulation, collars as well as the impregnation, yoking and skinning procedures have been tested using Mechanical Models (MM).

The Mechanical Model #1 is a 165mm long slice of the magnet straight section including the collared coil, the iron yoke and the skin (see Fig. 2a). The model design, fabrication procedure and room temperature (300 K) test results are reported in [7].

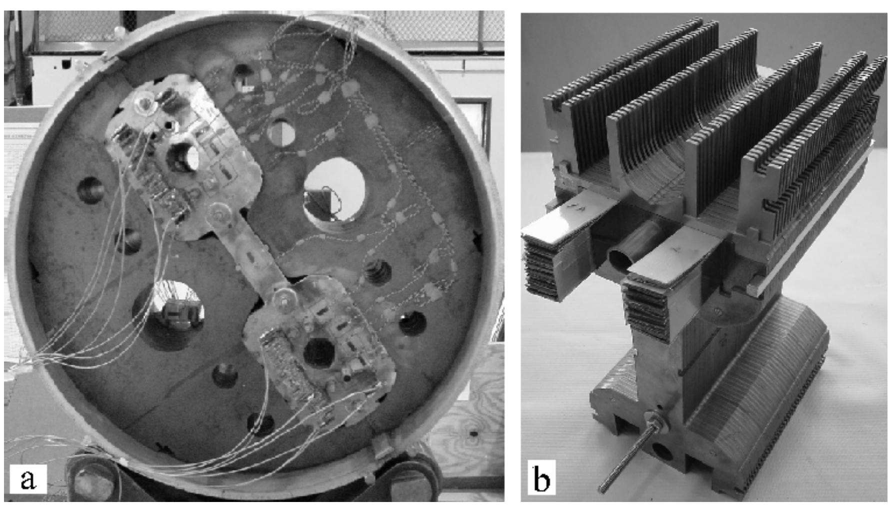

Fig. 2. Instrumented Mechanical Model #1 (a) and Mechanical Model #2 (b).

The Mechanical Model #1 was cooled down in liquid Nitrogen to 77 K and the tests of the electrical insulation were repeated. The lowest coil-to-ground breakdown voltage was higher than 3 kV and turn-to-turn voltage was higher than 2.5 kV.
The Mechanical Model #1 was instrumented with resistive gauges installed on the collar, the yoke and the skin (see Fig 2a). After skin welding several strain gauges was added on the coil polished edges in two pole (W1, W3) and midplane (W2) blocks and stress measurements were performed at both temperatures (300K and 77 K).

The final coil block size prior impregnation has been calculated base on ten-stacks measurements at 5-10MPa pressures.

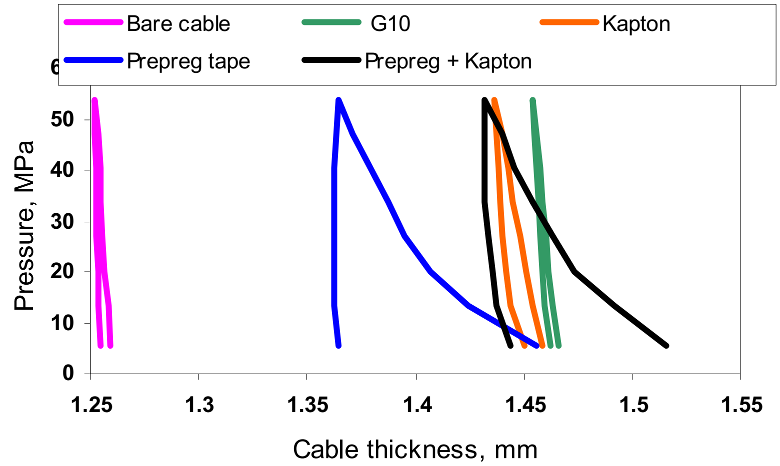

Figure 3. Ten-stack data

The final coil size was smaller than the structural windows geometry due to thickness variations in the insulation scheme and in the cable dimensions. The epoxy impregnation process follows by the collaring, only fixed the coil dimensions, given by window cavity. So, basically no vertical pre-stress was applied to the coils after impregnation.
The next process of skin welding increased coil side load by 40-50MPa.

The data on cool-down stress reduction in horizontal-X and vertical-Y directions for the coil blocks are summarized in Table I.

TABLE I
Coil Stress Data From Resistive Gauges (MPa)

X-direction			Y direction			
W2	W1	W2	W2	W1	W2	W3
12	17	17	-26	-22	-26	-32

The coil stress loss in Y-direction was in the range of 22-32MPa. These numbers were chosen as a target for coil warm pre-stress. Additionally 12-17MPa in X-direction compressed the coils due to skin shrinkage. The measured and calculated data for skin collar and yoke gauges are reported in Table II.

TABLE II
SKIN, COLLAR AND YOKE STRESS MEASUREMENTS (MPA)
(The FEA Prediction Are Given In The Parenthesis)

Condition	Skin	Collar	Yoke
Skin welding	160 (130)	-	-
Cool down to 77K	285 (310)	60	72-110 (100)

As can be seen, after cool-down the skin tension increased from 160 MPa to 285 MPa and the collar and yoke gauges showed compression of 60 MPa and 70-110 MPa respectively.

The FE model predicts the experimental data reasonably well for the yoke and the skin. The coil data need additional verification since un-reacted cables have been used in the model.

Based on the results of the cable insulation study performed on Mechanical Model #1 the spacer-type double-layer insulation [7] has been chosen for further testing in the racetrack and in the next mechanical model.

The coil size with modified insulation has been optimized on the Mechanical Model #2. The question was: how big fluffiness of the coil winding may be compressed down during collaring without exceeding 150MPa stress level on the reacted cable and archiving target warm pre-stress 20-30MPa?

The stacks of the 18 reacted ITER cable with ground insulation were locked by the laminated packs with the keys and the central tube as shown in Fig.2b. Capacitance gauges were used to control the coil vertical stress.

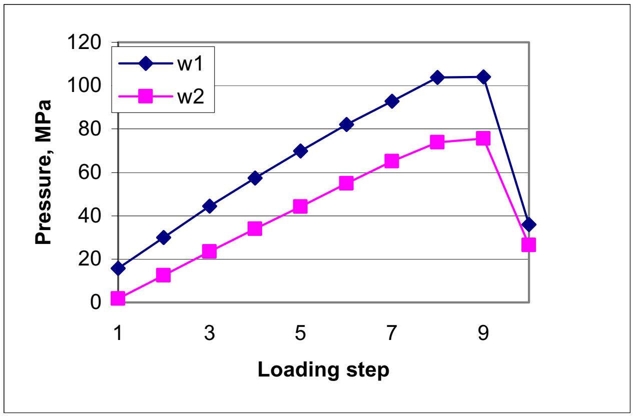

Figure 4. Mechanical Model#2 data

The oversized by 0.35mm (~0.02mm of winding fluffiness per turn) stack has been compressed to 80-100MPa during tube insertion. The stress in the coil block reduced to 30 MPa after spring back and a day later goes down to zero after creeping of soft B-stage glass tape.

It will be hard to achieve 20-30MPa target pre-stress in the coil after collaring, insulation creeping, epoxy liquefying and solidification (impregnation process) and do not exceed 150MPa of coil pick stress for the chosen insulation. Definitely, optimization work is needed for the cable insulation.

Therefore for the technological model, the dimensions of the coil blocks (at 5MPa) equal to the structural windows (without ground insulation) in the magnet were chosen as the coil target size after winding.

IV. Technological Model

To test the fabrication tooling and assembly procedures, an 800-mm long technological model has been recently built using reacted Nb_3Sn cable and real magnet components. Since all parts used in the technological model (except the cable) will be used in the planned short model, the magnet assembly was performed up to the impregnation stage (collared coil stage).

A. Superconducting Cable

The cable for the technological model was made of 60 Nb_3Sn strands with a diameter of 0.7 mm. Intermagnetics General Corporation (IGC) produced the strand using Internal Tin Diffusion process developed for ITER conductor. A 300-m long piece of 22.22-mm wide and 1.35-mm thick cable was fabricated at LBNL using synthetic oil and active turks-head fixture.

For strand reaction two 120-m long pieces of cable were wound on two single-layer metallic spools together with a mica-glass tape in order to prevent turn sintering during heat treatment. The reaction spools had the diameter that is a factor of two larger than the minimum diameter in the coil ends. That allows minimizing the bending strain of the cable during winding.

The cable was reacted in Argon atmosphere inside a retort following the schedule: ramp at 6°C/h up to 215°C, on hold for 175 h; ramp at 15°C/h up to 340°C, on hold for 120 h; ramp at 25°C/h up to 575°C, on hold for 160 h; ramp at 25°C/h up to 700°C, on hold for 30 h.

In order to determine the size of the cable after reaction, two cables made of different strands, IGC used in the technological model and OST to be used in the common coil model, have been measured before and after the heat treatment cycle.

The data measured without tension of cable samples and averaged for 15 points are shown in Table III.

TABLE III
Cable Expunction After Reaction

Conductor	Width, mm Before reaction and After		Thickness, mm Before reaction and After	
IGC	22.27	22.43	1.28	1.32
OST	22.32	22.68	1.25	1.27

For IGC cable the width increased by 0.7% and the thickness increased by 3%. The OST cable increased by 1.6% in both dimensions.

B. Insulation

Turn-to-turn insulation was chosen based on the test results obtained from the mechanical models and the racetrack [6], [7]. The spacer-type insulation used instead of wrapped one. It's minimized a risk of cable degradation due to wrapping and cable re-spooling. The insulation consists of two tapes with the same width as the cable: a 165-µm thick pre-impregnated glass tape and a 75 µm thick Kapton tape.

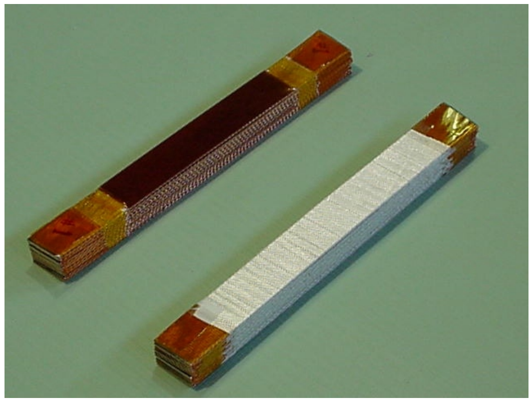

Figure 5. Cable insulation: Kapton strips and S-2 glass tape.

The pre-selected (by required thickness) glass tape had two splice joints due to short piece length. The ~15-mm long overlap junction has the same thickness as the tape after heating and compression in the splicing fixture. Both 110-m long glass and Kapton tapes were wound together on the same spool.

The ground insulation has been placed around all conductor blocks in the magnet. The cable had slightly oversized dimension in width. Therefore a nominal thickness of side ground insulation was reduced for winding convenience by 250 µm by using a combination of 0.5 mm thick G10 sheets and 0.25 mm Kapton film.

C. Splice Joint

For simultaneous winding of both coils into the support structure the two Nb_3Sn cables have to be spliced preliminary. The splicing was performed in a special fixture after both spools were installed on two tensioners. The cables were joined using two U-shaped pre-reacted 30-strand Nb_3Sn connectors and two copper stabilizers. The fixture provides the final shape of the splice as shown in Fig.6a, b.

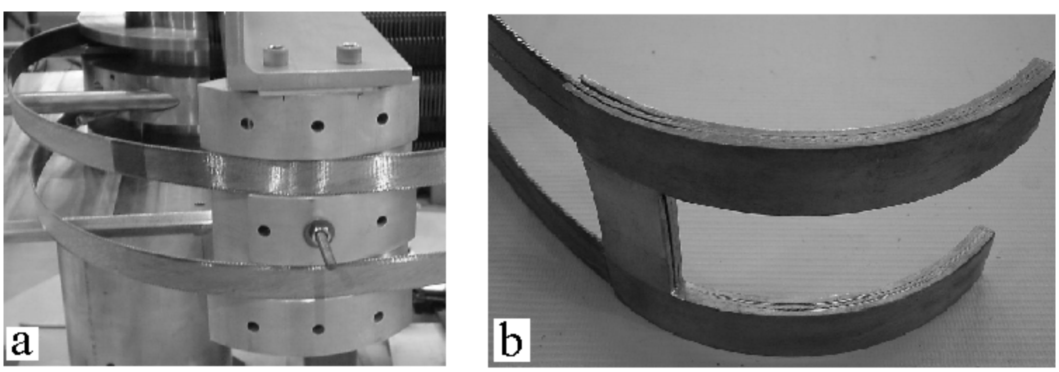

Fig. 6. Cable splice fixture (a) and cable splice (b) ready for installation.

D. Coil Winding

One coil consists of 3 blocks: 18, 22 and 18 turns. Each block was wound inside the windows formed by the collar laminations, the stainless steel ends, and locked by keys or screws (Fig.7).

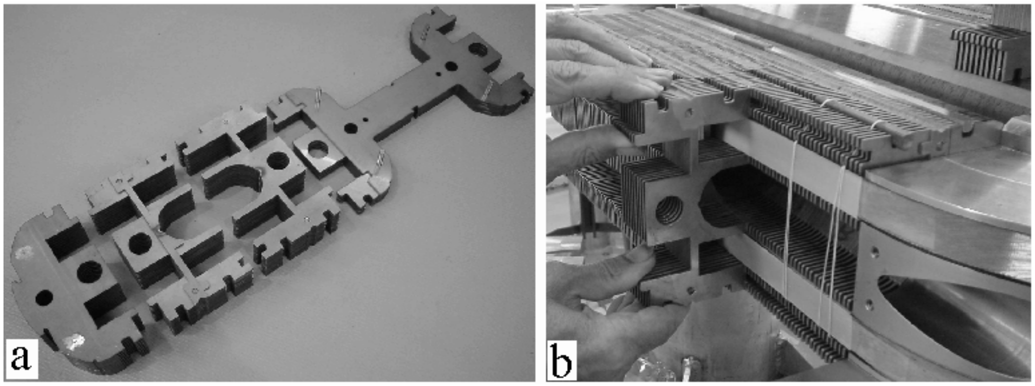

Fig. 7. Collar lamination packs (a) and pack insertion during winding (b).

Alternated laminations were assembled in ~38 mm long (20 laminations) packs using two pins as a base. Thin 0.1 mm thick SS washers separate laminations in the pack and provides path for epoxy during impregnation. The structure provides the proper positioning for the insulation tapes and the cables.

The insulated splice was carefully inserted in the splice slot on the lead end of the winding mandrel avoiding extreme cable bending. Four independent tensioners show in Fig. 8, were used to apply a tension of 90 N to each cable and 133 N to the insulations.

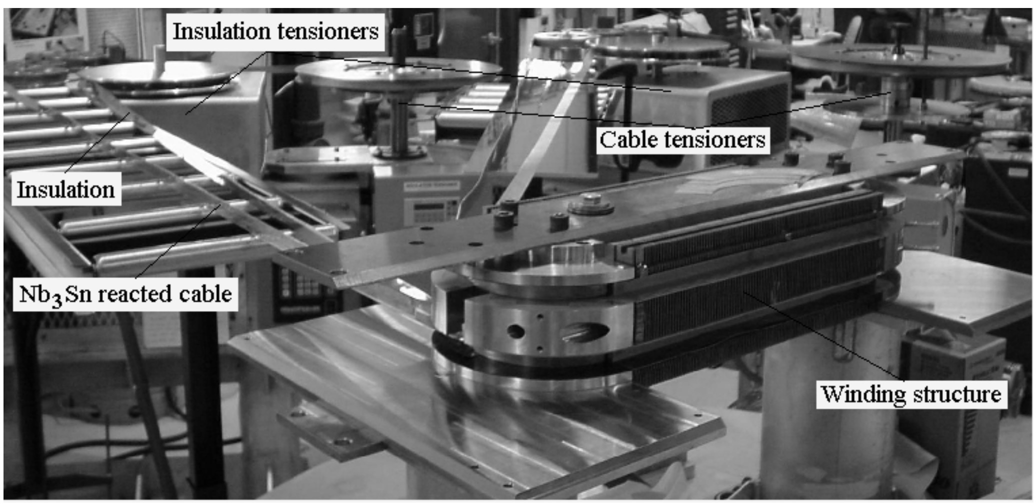

Fig. 8. Coil winding setup.

The insulation strips are wound together with the bare cable. The strip is sufficiently strong to be wound under a higher tension than the cable. It is reduces a risk of cable collapse and strand pop out, and lowers the coil spring back during winding. Side pushers had been used as well to achieve compact winding. To insert the keys the entire straight section was compressed from both sides using a collaring fixture. Then the fixture was removed for next coil blocks winding. Both coils were successfully wound and locked simultaneously block-by-block.

E. Magnet Leads

After winding, each Nb_3Sn lead cable was spliced with two NbTi cables and two stabilizing copper strips. The splicing procedure was identical to the lead splicing procedure developed for the racetrack models [5], [6]. The 150-mm long splices are placed in the lead end block such that about half of each splice is outside of the collared coil and is being in direct contact with liquid He, shown in Fig.9.

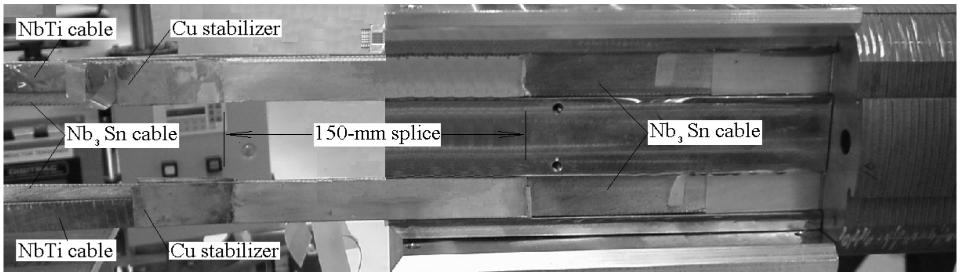

Fig. 9. Cable lead splices.

F. Impregnation fixture

The completed collared coil was assembled in the impregnation box, which provides the final alignment. The assembled and prepared for epoxy impregnation common coil collared coil shown in Fig.10.

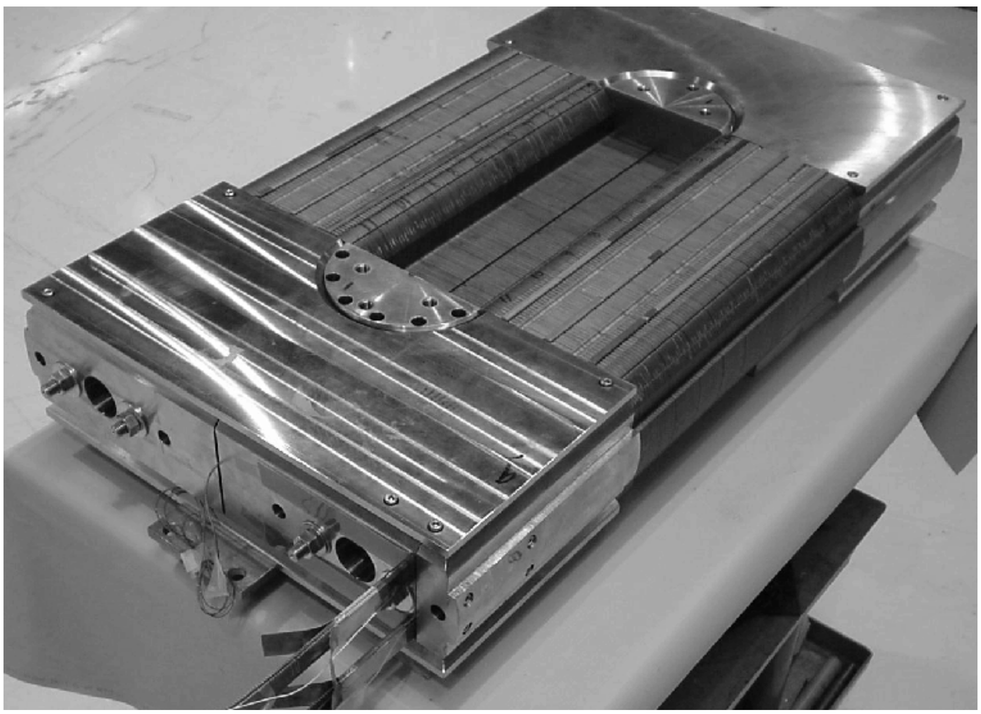

Fig. 10. Common coil technological model.

V. CONCLUSION

The design of a single-layer common coil dipole based on Nb_3Sn conductor and the react-and-wind technology was completed at Fermilab. The magnet mechanical concept and the assembly procedures were verified on the mechanical and technological models. The fabrication of 800 mm long Nb_3Sn Common Coil Dipole magnets is underway. Testing of the first common coil model magnet is planned for 2003.

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